CHAPTER 2

# The Role of Soil Tillage for Soil Structure

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## CONTENTS



## 2.1 FUNCTIONS OF SOIL STRUCTURE IN THE SOIL COMPARTMENT OF AGRO-ECOSYSTEMS

Soils are characterized by an intensive spatial and functional overlap of geosphere, hydrosphere, atmosphere, and biosphere.[37] They are objects in space and time with unique properties and behavior that justify their study as natural bodies of considerable scientific interest. In a functional sense, soils are compartments of ecosystems. They comprise well-organized networks of interacting physical, chemical,

and biological subsystems and may be regarded as complex systems. The functional and ecological relevance of soils is a direct result of their role in natural as well as in agricultural systems.[95] Soil structure plays a crucial role in this context. Well-known problems associated with soil structure are surface sealing, crust formation,[69] soil erosion,[63] and groundwater pollution caused by rapid transport processes in preferential flow systems like macropores.[49] Therefore, the maintenance of soil structure must be considered an essential part of any sustainable soil management system, should soil fertility be preserved in the long-term.[53]

The ecological functions of soil structure comprise water, matter, and heat dynamics as well as several mechanical properties like bulk density or penetration resistance. The different functions have far-reaching effects on the soil environment and consequently on the associated agro-ecosystems. The spatial arrangement of primary particles, for instance, defines the pore system, which in turn determines water and nutrient availability on the one hand and parameter functions for water, nutrient, pollutant, and gas transport in soils on the other.[20,14] Gas transport properties of porous media are very important for plant root oxygen supply, gaseous losses of pesticides, $N_2O$ and $N_2$ fluxes as a result of denitrification, and $NH_3$ from topsoil.[83] Gas permeabilities are especially susceptible to changes in soil structure. Further, the spatial arrangement of the solid particles, together with the mineral composition, determines the spatial distribution and the physicochemical properties of reactive surfaces in the soil. Mobilization and immobilization of nutrients and pollutants are processes that are highly controlled by surface interactions.[80,52] The mechanical properties of soil structure determine the penetrability of the soil by plant roots and the anchorage of the root system. To summarize, soil structure is an essential property of the soil system that defines the environment for both plant roots and edaphon. Consequently, tillage schemes may be regarded as an important tool in arable soils that have the potential for maintaining an optimal and stable soil structure.[36]

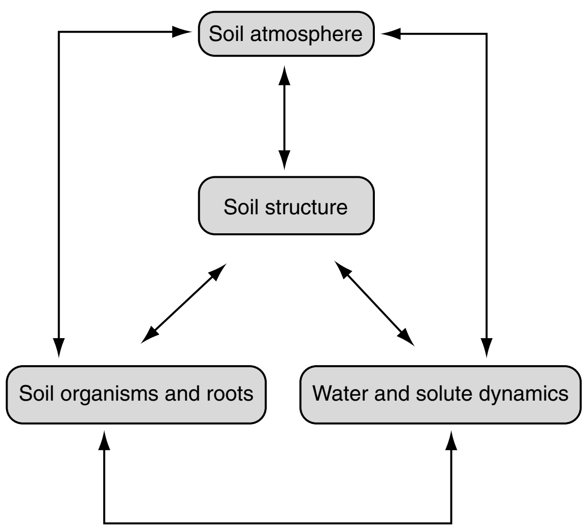


**Figure 2.1** Ecological functions of soil structure in the soil compartment of ecosystems.

## 2.2 SOIL STRUCTURE AND THE SOIL PORE SYSTEM

### 2.2.1 Components of Soil Structure

Soil structure in a general sense can be defined as the spatial arrangement of primary particles and the corresponding pore system of the soil. While the combination and interaction of the solid, liquid, and sometimes gaseous phase is important for properties like carrying capacity, trafficability, and penetrability of soils, the transport behavior of soils for water, nutrients, pollutants, and gases is mainly determined by the pore system. Particle and pore distribution simultaneously determine the spatial arrangement of the pore–solid interface, which greatly influences the reactivity of soils.

Elements that make up soil structure include macroscopic cracks, voids, holes, and tubes, as well as crusts and soil aggregates that divide the total pore volume in an intra-aggregate and an interaggregate space.[52] The intra-aggregate pore system is characterized mainly by topological parameters like tortuosity, which is the ratio of the mean true pore length of single pores and the shortest connection of two points; continuity, which characterizes whether or not two pore regions are contiguous to one another; restrictivity, which refers to the variability of the pore radius of single pores; and connectivity, which is the intensity of the connections within the pore network.[14]

Continuity is sometimes defined as the inverse of tortuosity, but it is clear from Figure 2.2 that continuity and tortuosity are completely independent of each other. In most practical situations, a combined effective parameter is estimated in the context of transport experiments with undisturbed soil-column experiments. On the other hand, connectivity is a more general and useful pore property that can be quantified by micromorphological methods.[91,92]

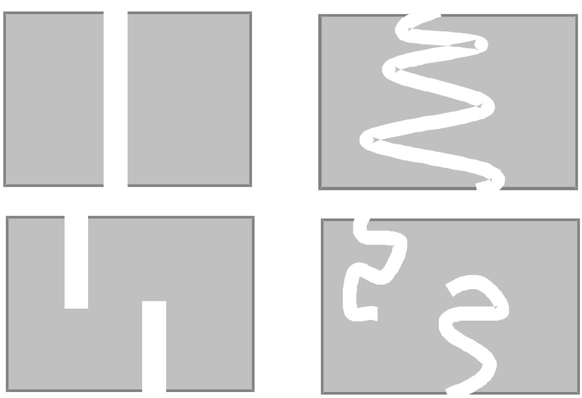

**Figure 2.2** Tortuosity and continuity of pores; top left: nontortuous and continuous pore; top right: tortuous and continuous pore; bottom left: nontortuous and noncontinuous pore; bottom right: tortuous and noncontinuous pore.

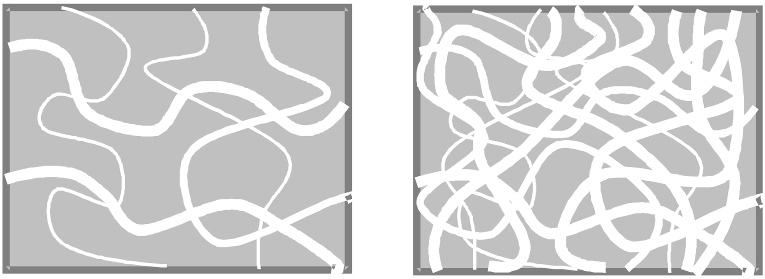

**Figure 2.3** Connectivity of a pore system; left: low connectivity; right: high connectivity.

### 2.2.2 Structure Formation

Sustainable soil management philosophy is ultimately based on an understanding of structure-forming processes of soils. This is an essential prerequisite for any decision on appropriate tillage systems. It must take into account the actual soil state and the meteorological boundary conditions so that soil degradation can be avoided and optimal structure maintained.

Formation of soil structure is known to be a function of both abiotic and biotic factors at a site. Cracks, voids, crusts, and soil aggregates like polyhedral blocklike peds, prismatic and columnar structures, or plates are formed within wetting and drying cycles[26,69] by shrinking and swelling processes.[37,76] Other important factors are frost and thawing cycles,[13,55] dispersion and flocculation of clay minerals, and external forces (soil tillage, compaction by agricultural machinery).[50,34,38] Biological activity, on the other hand, comprises microbial activity,[2,76,94] root growth, activity of earthworms,[68,77,98] and other soil-dwelling animals, both invertebrates and even vertebrates. (A systematic approach to determine soil structure is given in Reference 6). Creep processes are often observed in sloped areas but are mainly important in periglacial regions[41] or marginal farming areas with steep slopes and thus often less relevant for agriculture.

As a result of the spatially distributed structure-forming processes, soil structure cannot be regarded as homogeneous. Even within visually homogeneous soil horizons the spatial variability of soil properties may be considerable and must be regarded as a substantial property of the soil system.[52] Thus, spatial variability of the pore network and related parameters like water and air permeability functions are themselves inherent elements of soil structure and largely determine its functional behavior. Effects of spatial variability have been analyzed in several studies.[39,67,74,75,93] Interesting results of these studies show that soil variability cannot be neglected with regard to transport processes (nutrients and pollutants) and that, in most cases, averaging of soil transport parameters will produce misleading results compared to flux averaging of the heterogeneous system.

Soil tillage affects biotic and abiotic processes of soil structure formation—directly, by modifying structural properties like cracks, aggregates, and connectivity, and indirectly, by changing the conditions for abiotic and biotic processes in the soil, e.g., aeration, thermal behavior, penetrability, etc.

### 2.2.3 Forces Acting on Soil Structure

Structural dynamics are the result of forces like external load, shearing, slaking,[54] and the resistance of structural elements against plastic deformation and dislocation. The main factors of soil stability may be divided into two major groups: one that is more or less stable in time and the other that is fluctuating and largely depends on management measures like fertilization. This affects the development of the root system and the content of easily decomposable organic matter, and soil tillage, which impacts aggregate size distribution and aggregate stability. The first group comprises the mineralogical composition of the soil, particle shapes, particle size distribution and arrangement, presence of cementing agents, pore size distribution, and the content of stable organic compounds. The second group is made up of fresh organic matter, water content, salt concentration, composition of exchangeable cations on the exchange complex, the thickness of the electrical double layer (as a result of salt concentration and cations on the exchange complex), and biological activity, especially earthworm and bacterial activity, which accounts for the generation of so-called clay-humus complexes. These are stable associations of organic material and clay minerals with high cation exchange capacities.[37,76]

There are two different locations in a soil profile where tillage can have considerable impact on soil structure: the soil surface and the zone of stress propagation in the underlying soil body. The soil–atmosphere interface is highly affected by rainstorms and drying–wetting cycles, resulting in sealing and crusting of the soil surface[69] with considerable impact on seed germination, aeration, and erosion. These processes occur mainly when the soil surface is directly exposed to the atmosphere. Thus, coverage by plants and organic residues, high surface roughness, and minimizing exposure time are features that are effective in reducing these negative near-surface effects.[63]

Machine load, vibrations, and shear forces caused by cutting, smearing, and rotating blades are other sources of structural damage that are located mainly in the plow zone, but by pressure propagation may also have effects in deeper zones. These effects can be discussed partly in terms of the stress strain concept, which is well developed in soil mechanics (see Reference 96). Simulation methods have been developed for the calculation of normal and shear stress distributions in depth as a function of wheel geometry, machine load, and soil properties like wetness and aggregation.[29,34,87,88] However, the stress–strain concept is not always appropriate for soils, and sometimes rheological approaches are more suitable for situations where nonlinear relations, plastic behavior, or creep processes predominate.[35,37]

Models need parameters and validation data. Unfortunately, stress and deformation measurements exhibit some serious problems. Recent studies[29,89] show that soil-embedded sensors may disturb the stress field and thus produce misleading results.

Interactions between soil and machinery may be direct or indirect in nature in that they influence aggregate forming and stabilizing processes. Examples of direct interactions are compaction by the load of heavy machines transmitted by the tread bars of wheels; rupture; shearing and smearing caused by shares, heels, moldboards, and coulters; and the crashing effects of rotating blades and tines. Direct interactions have been extensively studied in soil mechanics. Hammel[34] investigated the effects of different wheel profiles and tread bar patterns on soil compaction. He used the

SOCOMOD stress model[87] to predict the stress propagation in soil. Shen and Kushwaha[79] provided theory and numerical algorithms for the direct calculation of stress and deformation by soil tillage equipment. They presented elastic, plastic, and dynamic (visco elastic, elasto-viscoplastic) models as well as models for the simulation of soil–metal interfaces. They use a finite element approach and present several examples of soil–tool interactions. Unfortunately, this type of modeling gives little information about impacts on intrinsic properties of the pore system like water retention curves and permeability functions. Models that are capable of calculating changes in pore size distribution and its effects on soil physical behavior due to external forces are rare and still the subject of research.[29]

## 2.3 ASSESSMENT OF SOIL STRUCTURE AND TILLAGE EFFECTS

The first step in assessing soil structure is to conduct a visual inspection using an appropriate classification system (see Reference 6) or experience. Although this is a qualitative rather than a quantitative procedure, it gives not only a first impression of the structural elements but also allows, through human expertise, a quick appraisal of the overall complexity of the soil system. There are also quantitative field methods such as penetrometers, shear vanes, or field rainfall simulators[37,48] that enable quick measurements of simple mechanical parameters related to soil structure, root growth, and surface sealing. Unfortunately, they are not standardized and are prone to personal biases and errors, so that the comparability of different studies is rather limited. They are, however, very useful within the same study as long as the experimenter remains the same and moisture contents are similar between plots. Other field methods that allow the assessment of structural effects are infiltration methods like the double-ring infiltrometer, the Guelph permeameter for the measurement of the field saturated hydraulic conductivity, tension infiltrometers for unsaturated conductivities, and *in situ* air permeameters.[6,18,48,85] A comparison of ring infiltration and tension infiltration rates allows for conclusions about the potential ratio of matrix and macropore flow.[27] A direct visualization of preferential pathways is possible using dye tracers. This methodology has been used increasingly in recent years to identify soils that are susceptible to preferential flow.[21,25,78]

A group of methods exists for laboratory assessments. Useful characterization of soil structure is already possible by basic parameters like particle density, bulk density, porosity, and void ratio.[85] Hakansson and Lipiec[32] gave a review of the usefulness of relative bulk density values in studies of soil structure and soil compaction. In particular, they discussed a parameter called “degree of compactness” and stressed the robustness of an optimal value against variations of soil composition and the relation to critical values of penetration resistance and air-filled porosity. Other simple methods to characterize the pore system are particle and aggregate size distributions, water stable aggregates, diffusion experiments, and the measurement of transport parameters like saturated and unsaturated hydraulic conductivity or air permeability.[48] Unfortunately, one of the frequent but unavoidable problems of laboratory methods is that the representary elementary

volume REV* of the soil is not met.[52] It leads not only to a high variability of the measured values, but also, what is even worse, to a change in continuity of the pore system by the sampling process itself. Laboratory measurements of transport parameters are not very reliable and often of little benefit for field studies.

More detailed information is available by determining the equivalent pore size distribution of soils, which is derived in most cases from the capillary rise equation.[37] In this approach, the soil is assumed to be composed of a set of different-sized straight cylindrical glass tubes with behavior identical to that of natural soils when exposed to a pore pressure gradient. Though this is a very abstract view of a soil porous medium, the obtained information is reliable, reproducible, and interpretable for most practical field studies. Further, pore size distributions can be used as pedotransfer functions** in order to determine hydraulic soil parameters (see, for example, References 40 and 62).

Advanced and recent methodologies for pore system assessments comprise the determination of the EPC (Euler Poincarè Characteristics).[91] This is based on serial sections through impregnated samples that may also be used for the generation of virtual pore networks for computer-based studies[92] and, in addition, in-field tracer studies aiming at identification and behavior of preferential flow systems such as macropore flow, heterogeneous flow, or funnel flow.[21,25] As these systems are influenced by both biological activity and abiotic processes, they are quite susceptible to changes in tillage regime and shifts within the upper boundary of the soil system, e.g., by fertilization (crop growth), irrigation, or cover crops.[63]

Another promising approach to characterizing pore geometry is fractal geometry. Gimenez et al.[28] applied fractal geometry to characterize structural units in freshly tilled soils. Jozefaciuk et al.[44] determined fractal dimensions in pore systems of brown forest soil to assess the effects of different tillage practices. A new technology to visualize soil structure and measure structural parameters is computer tomography. Werner and Werner[94] showed the potential of this technology in a recent study on compaction and recovery of soil structure in a silty clay soil.

Soil mechanical methods are used to determine the propagation of stress and strain in the soil body. Several sensor types have been developed that measure the different components of stress as a function of the distance of the machine load and the tire.[34,89] The idea of this approach is to use the measurements for calibrations of simulation models and to utilize them to optimize surface pressure, tire size, and elastomechanical properties of the wheels.[34,87,88] Unfortunately, the stiffness of the sensor material may affect the stress field in the soil, thereby restricting the reliability and usefulness of the results.[29]

Simulation of direct soil-machine interactions is performed by elastic, plastic, and dynamic models based on linear and nonlinear stress strain theory. It involves

* The REV is the minimum soil volume that contains all typical structures of a given soil or soil horizon and thus minimizes the variability of the target variable under study. In general, the REV has a different magnitude for different soil properties. By taking samples that do not meet the REV, the cutting of soil cores brings about a certain percentage of pores appearing to be continuous that are discontinuous in the undisturbed soil body.

** Pedotransfer functions are empirical or physically based functions that allow the estimation of properties like sorption characteristics and permeability functions that are difficult to measure from easily measurable soil properties like bulk density, organic C content, texture, and water retention curve.

tensor algebra and analysis and is not detailed here. The resulting system equations are in general numerically solved by finite element analysis.[79] Roger-Estrade et al.[72] recently developed a compartmental model to simulate temporal changes in soil structure. They used the proportion of severely compacted clods in the ploughed layer as an indicator of the effects of cropping systems on soil structure. Their model may be used to assess impacts on soil structure caused by technical changes.

## 2.4 SIGNIFICANCE OF SOIL STRUCTURE AND SOIL TILLAGE FOR PRODUCTIVITY OF AGRICULTURAL LAND

While most soil degradation in the world is of a chemical nature, Lal and Stewart[53] point out that there are also severe soil physical limitations to productivity including factors like seal and crust formation, compaction, and poor trafficability. Worldwide, especially Alfisols, Ultisols, and Vertisols exhibit poor soil physical properties with high erosion risks (see References 19 and 53).

Moderate to severe damage by soil erosion is observed on about 80% of agricultural land worldwide.[53] About 17% of potentially arable land had lost its agronomic value by erosion over a 45-year period ending in 1993.[9] Tillage practices play a crucial role in soil conservation. With respect to soil erosion problems, several tillage systems are in use in order to reduce soil losses by erosion. No-tillage, strip tillage, mulch tillage, and reduced or minimum tillage, among others, are the most important systems.[63] Ehlers et al.[16] in a field experiment in Germany compared moldboard plowing with conservation tillage on a silty soil. They found positive effects of conservation tillage on root growth and yield but stressed that the better resistance of the conservation tillage is not enough to completely avoid damaging effects by heavy machinery. Arshad et al.[4] found improvements in water retention in fields with no-tillage in northwestern Canada and, as a consequence, higher barley yields in years with low precipitation. They concluded from their studies that no-tillage may be a viable tool to improve soil quality under the cold semiarid conditions of Northwestern Canada.

Classical aims of tillage systems in agriculture are to create good seed-to-soil contact and an appropriate root environment in topsoil; to provide optimal conditions for subsequent crop with respect to water, air, and heat budget; and to control weed infestation. Under practical farm conditions these goals are too often not met, and structural degradation can be observed. Commonly observed problems with conservation tillage, especially with no-tillage and minimum tillage, include difficulties with weed control and, as a consequence of open macropore systems, increased pesticide leaching to groundwater. Masse et al.[58] detected that Atrazine (chloro-2 ethylamino-6 triazine-1,3,5) concentrations of shallow groundwater were significantly higher under no-tillage compared to conventional tillage. No-tillage effects were found for Metolachlor concentrations on the same site. Similar results for atrazin distributions in the profile one day after application were observed by Zanin et al.[97] In the case of Isoproturon, they also detected rapid translocation but with no differences between no-tillage and conventional tillage. Unfortunately, they restricted their investigations to a maximum depth of 30 cm. Further, their results proved to be site-dependent. On other sites, Isoproturon and Monomethyl-isoproturon did not show rapid transport to

deeper horizons. With respect to nitrogen, Mehdi and Madramootoo[60] concluded from their studies that conservation tillage practices like reduced tillage, no-till, and residue management may be an efficient tool for reducing $NO_3$ -N levels in soil profiles as long as urea fertilizer is used. The impact of rototillage on short-term dynamics of nitrogen and microbial activity was studied by Calderon et al.[11] The authors concluded from their results that short-term changes in nutrient dynamics caused by tillage may result in increased denitrification and nitrate leaching rates.

To summarize, an additional challenge in recent years concerning soil tillage has been groundwater protection, especially in middle Europe due to low tolerance levels of pesticides. In this context, structural heterogeneity in all its varieties plays a crucial role.[12,25,27,67] Problems associated with this complex are far from fully understood and are still an open subject of research.

However, macropores may also exhibit positive effects with regard to groundwater quality. According to a hypothesis of Teixeira,[85] under natural conditions of the humid tropics, the soil structure of a clayey Ferralsol develops in coevolution with the root system of prevailing plant species in the rain forest, resulting in an optimal structure that maximizes nutrient efficiency and minimizes unproductive losses. Nutrients remain in the soil matrix while water flow occurs in macropores and bypasses the microstructure. Flux densities in the soil matrix are thus reduced and travel times of nutrients through the root zone increased. In contrast to this, conventional agriculture exerts mostly adverse changes in soil structure that tend to degrade environmental conditions for root development and soil organisms, thereby decreasing the macropore system and enforcing nutrient losses and groundwater pollution by increasing flux densities in the soil matrix. Conventional management systems often result in increased plastic deformation,[50,87] irreversible compaction,[38] and seal as well as crust formation.[54] This is mainly caused by an unsuitable use of heavy machines, application of heavier earth-penetrating tools, and rotating blades (rotovators). Progressive tillage systems should thus focus on avoiding such negative effects by careful adaptation of tillage regimes and tools to specific site conditions.

## 2.5 IMPACTS OF SOIL TILLAGE ON SOIL STRUCTURE

Tillage effects on soil structure differ according to the type of acting forces and the location of action. Direct impacts are destruction of aggregates, compaction, and unfavorable changes of pore size distribution and pore structure. This results in reduced hydraulic conductivity and air permeability. Shifts in soil physical conditions consequently induce negative modifications in soil environments, with serious impacts on plant roots and edaphic species, e.g., earthworms, enchytraeids, and microorganisms.[46] Reduced biological activity means fewer stable aggregates, a reduction of macroporosity, and, hence, negative feedback mechanisms for the soil structure. A schematic overview of tillage impacts on soil structure and resulting pedological and ecological implications is given in Figure 2.4. According to the nature and targets of involved forces, the deterioration of the soil–air interface or aggravation of transport behavior in the soil profile are the expected outcome. Tillage effects were

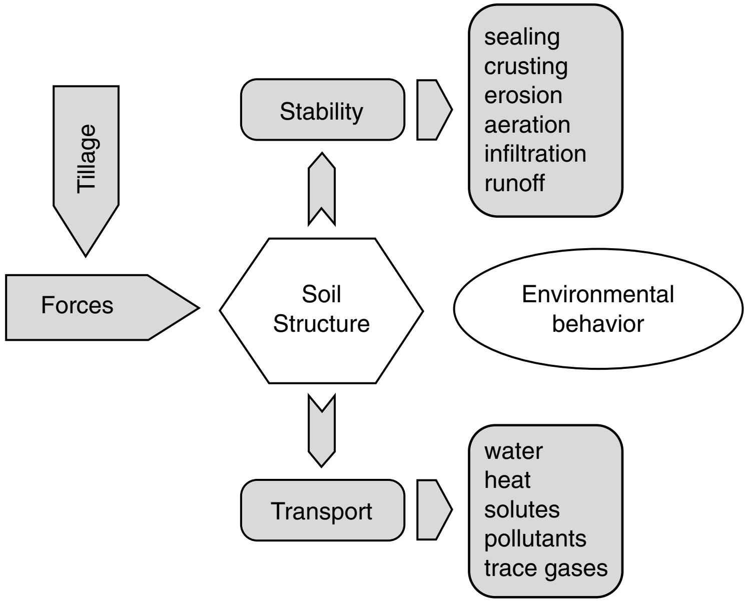


**Figure 2.4** Schematic representation of tillage, forces, effects on soil structure, and pedological and environmental consequences.

investigated in several studies that underline the importance and relevance of different tillage systems for structure development and maintenance.

A review of physical and biological effects of reduced tillage based on a long-term study in Germany is given by Tebruegge and During.[84] Their main conclusions are that reduced tillage and no-tillage had beneficial effects. They stress the potential of these systems to replace conventional ploughing systems in many cases under the temperate European climatic and pedological conditions. Some biological and ecological implications of tillage can be found in References 57, 73, and 46.

In field studies, porosity, bulk density, shear resistance (soil cohesion), and penetration resistance are simple and easily measurable parameters that are closely related to soil structure but are also affected by soil moisture content. Rampazzo and Mentler[70] found higher bulk density values, a decrease of total porosity, soil aggregate stability, and coarse pores in Austrian and Hungarian agricultural soils as a result of cultivation. They also observed a more crumbly structure in uncultivated fields compared to tilled soils. Similar results were reported by Bordovsky et al.[10] for the Texas rolling plains being characterized through rather low rainfall, crop residues, and low soil organic matter content for agricultural soils under dry-land and irrigated systems. According to their study, occasional deep subsoiling may be needed to reduce the effects of compaction.

Unger and Jones[86] studied the effects of stubble mulch tillage and no-tillage in several cropping systems for dry land with winter wheat and grain sorghum as the crops. Bulk density and penetration resistance were found to be lower in topsoil of the stubble mulch tillage treatment. No trends could be identified for deeper soil

layers. Their observations further led them to conclude that stable biopores reduced the effects on bulk densities among different no-till plots. According to their study, no-till soils developed a rigid structure independent of bulk density.

Krzic et al.[51] contrasted short-term responses of soil physical properties to fall and spring tillage against fall and no-spring tillage systems, with spring barley and winter wheat as winter cover crops. Despite differences in air-filled porosity, bulk density, and mechanical resistance, they concluded that fall tillage operations did not affect soil physical conditions for plant growth in a humid maritime climate.

As already mentioned, aggregate size distribution and aggregate stability provide important information on the susceptibility of soils to sealing, crusting, erosion, and soil aeration and respiration. Aggregate stability is highly affected by organic carbon and by C-management within agricultural systems. Angers[3] stated that accumulation of organic matter as a result of reduced or no-till conditions, perennial forage crops, or manure additions may increase the fraction of macroaggregates in soils.

In a long-term study on integrated and conventional agricultural management, El Titi[17] and Veneckel[90] measured considerably lower values of ΔGMD (difference of weighed mean aggregate size before and after wet sieving*) for the topsoil at 8 to 12 cm depth of the plots with reduced tillage. At greater depths (18–22 cm), the differences were less pronounced.

Stenberg et al.[82] studied effects of reduced tillage and lime on crop yield and soil physical and microbial properties in a weakly structured silty clay loam soil. In response to soil organic matter accumulation and enhanced microbial activity, aggregate stability was improved by a shallower tillage depth, while liming had little effect on soil structure variables.

In a field experiment in Germany, Wiermann et al.[96] investigated changes of soil mechanical properties induced by conservation tillage systems on a silty loam Luvisol. They detected a higher soil strength for the reduced tillage plots due to more robust aggregates. Further, they observed preserved fragments of channels in depths greater than 30 cm in conservation tillage and expected the conditions for structural recovery to be more favorable with this tillage.

Hallett et al.[33] focused on water repellency of aggregates, which is another important property of aggregate surfaces with implications for the resistance of soil structure against disruption by wetting, bypass flow, and surface runoff. They assessed a water-repellency index, R, and found that this value is highly affected by cultivation. In their study, soil aggregates were more repellent in no-till than in plowed soils.

From the above we can conclude that conventional tillage tends to have negative impacts on soil structure. Compared to reduced and no-tillage systems, conventional tillage results in reduced hydraulic conductivities, air permeabilities, and structure stability values. In contrast to this, reduced and no-till systems seem to be able to avoid negative impacts on plant roots and edaphic species. Increased biological activity will result in increased macroporosity values and a more rigid soil structure and thus contribute to an improved soil structure. On the other hand, increased macroporosity and stable macropore systems considerably influence the transport system of the soil, which will be discussed in the following section.

* ΔGMD (difference of weighed mean aggregate size before and after wet sieving) is a direct measure of aggregate stability against immersion and movement in water.

## 2.6 SOIL TILLAGE AND TRANSPORT PROCESSES IN SOILS

### 2.6.1 Transport in Structured Soils

Soil structure and its modification by different tillage systems is of special significance for the transport of water, nutrients, and pollutants in soils. In most cases, a pronounced establishment of micro- and macrostructural elements will lead to considerable amounts of water flow in preferential pathways. Such systems have been extensively studied by Flury,[22] Flury and Flühler,[23] and Flury et al.[24] One phenomenon in such systems is that the pore system exhibits two (or more) transport systems—a slow pore system where mainly matrix flux occurs and a fast system with preferential flow. Consequently, depending on the boundary conditions on the soil surface, nutrients bypass the root system in the fast transport system and contribute to groundwater pollution. On the other side, matrix flux is slowed down, and resident times are increased in the matrix compared to a system with no preferential flow. A visualization of these processes is possible using dye tracers that have been used intensively in recent research.[21,25] Two examples are shown in Figures 2.5 and 2.6 for a typical agricultural field with conventional tillage and a drained agricultural soil.

In the drained soil, vertically oriented holes of earthworms create a pronounced vertical anisotropy of hydraulic conductivites and completely alter the water-flow pattern around the tiles.

When dealing with preferential pathways, one must consider that macropores are an important source of preferential flow, but other special structural properties and boundary effects may also provide fast flow systems in soil. Generation and effects of macropore fluxes have been studied intensively by Beven and German[8] based on a kinematic wave approach. Jarvis[42,43] and Ludwig[56] developed a numerical model that could take into account macropore flow and the interaction of soil matrix and the macropore system. Such models have been tested in several field studies for

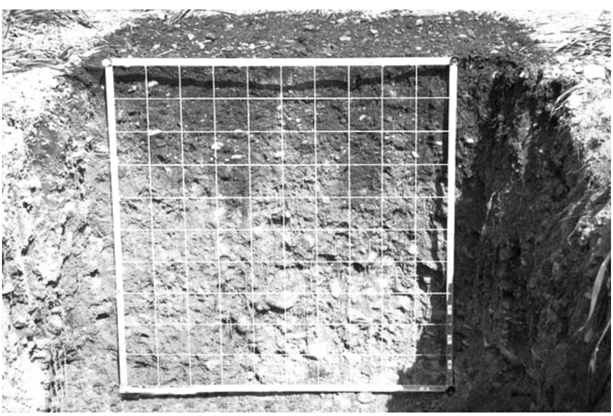

**Figure 2.5** Dye patterns after infiltration in an agricultural soil with conventional tillage.[24]

**Figure 2.6** Dye patterns after infiltration in agricultural soil with tile drains.[81]

their predicting capacity. Results were promising though still not completely convincing (see References 7 and 56). Similar patterns can result from heterogeneous spatial fields of soil hydraulic parameters. The resulting flow patterns depend on the degree of heterogenity, autocorrelation functions, anisotropic conditions, boundary conditions, and the initial water distribution in soil. In contrast to macropore, flux flow patterns caused by heterogeneous parameter fields are not stable but depend to a certain extent on the actual distribution of the water in the soil.[74]

Soil tillage systems have a pronounced impact on oriented structures in soils due to homogenization effects and interruption (conventional tillage) or promotion (reduced tillage) of vertical macropores like earthworm holes and crack systems. On the other hand, horizontal structures may be introduced by repeated machine load, vibrations, and smearing effects of plow shares. An important consequence of structure orientation for the soil's transport system is the resulting anisotropy of the pore network. Horizontal structures create horizontal anisotropy of water and solute transport parameters, while predominant vertical structures produce heterogeneous vertical flow patterns with accelerated peaks of preferential flow in vertical continuous structures and retarded transport in regions with low permeability.

A simulation example of the effect of anisotropy is shown in Figure 2.7 (vertical anisotropy) and Figure 2.8 (horizontal anisotropy).* Vertical anisotropy produces a much higher dispersion of the artificially introduced initially horizontal concentration peak line in 10 cm depth compared to horizontal anisotropy. While vertical anisotropy in most cases accelerates leaching of solutes to groundwater, horizontal anisotropy can enhance near-surface saturation of the soil and thus enforces surface runoff and soil erosion on slopes.

A crucial factor for bypass flow generation is the soil–air interface, which is defined by the state and stability of soil structure together with actual micrometeorological conditions like rainfall intensity, drop size, wind speed, etc. This interface

* Random walk simulation with 10000 Partikels, steady rate infiltration with 15 mm/d, sandy loam with van Genuchten parameterisation and a saturated conductivity of 106 cm/d; the conductivity fields were generated with an exponential covariance function; the degree of anisotropy was the same for horizontal and vertical anisotropy.

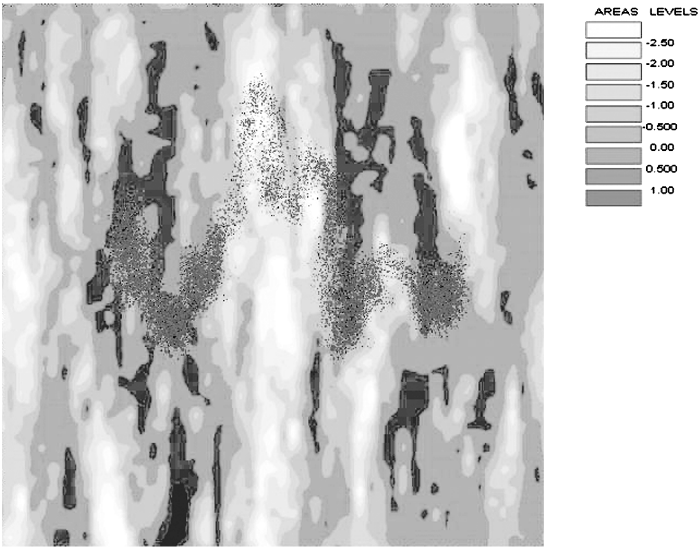


**Figure 2.7** Transport pattern in a sandy loam with vertical anisotropy of hydraulic conductivities after infiltration of 97.5 mm water; the initial position of the solute was a horizontal peak line in 10 cm depth; profile depth is 100 cm; the background color visualizes the total flux density of water (transport simulation with HTS).[67]

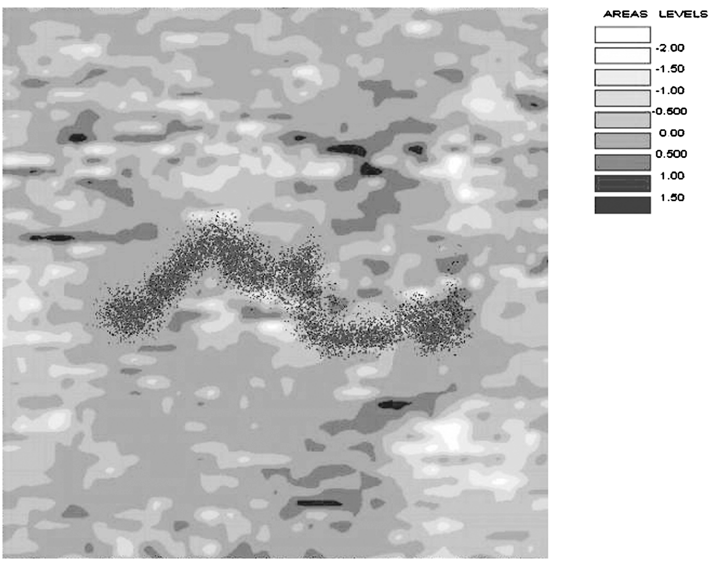


**Figure 2.8** Transport pattern in a sandy loam with horizontal anisotropy of hydraulic conductivities after infiltration of 97.5 mm water; the initial position of the solute was a horizontal peak line in 10 cm depth; profile depth is 100 cm; the background color visualizes the total flux density of water (transport simulation with HTS).[67]

is very susceptible to soil-management measures. Soil tillage in particular has a significant impact on surface processes like sealing and crusting. Consequently, when tillage systems are optimized with respect to aggregate stability and aggregate size distribution, soil hydraulic processes like runoff, infiltration, and preferential flow may be regulated in order to reduce environmental damages like soil erosion and groundwater pollution. Similarly, evaporation and the emission of gases like $NH_3$, trace gases, and herbicides may be affected by soil-management procedures with impact on the continuity of air-filled pores near the soil surface.[59,65]

### 2.6.2 Impact of Soil Tillage on Water and Solute Transport in Soils

Modifications of soil structure by soil tillage cause changes in conductivity and permeability characteristics for water, heat, and air flow, as well as solute transport in soils and their spatial distribution. This results in transport patterns reflecting the presence of macropore systems and spatial heterogeneity of hydraulic material functions of the porous media. Reduced tillage often results in an increase in macroporosity saturated conductivity and infiltration capacity, reduced surface runoff, and, hence, reduced erosion risks.[1,17,63,90] On the other hand, macroporous systems are reported to be partly responsible for groundwater pollution by agrochemicals.[7,20,24,59]

In column experiments, Miller et al.[61] analyzed the potential of tillage practices to influence preferential leaching. They utilized the two-region (mobile/immobile water) model of solute transport to compare preferential leaching under conventional and no-tillage in fields with clay–loamy texture. They found similar values of mobile and immobile fractions for both tillage systems and concluded that the different tillage systems did not affect the ratio between fast and slow transport systems.

In contrast to these findings, double-ring infiltrometer experiments in the long-term "Lautenbacher Hof" experiment on integrated and conventional farming schemes clearly demonstrated the homogenization effect of tillage in the topsoil of the conventional system (Figure 2.9) and the heterogeneous infiltration patterns caused by macropores in the integrated fields with reduced tillage (Figure 2.10) under field conditions. Figure 2.11 focuses on the transport in a single worm hole and shows the potential positive effect on infiltration when the soil surface is exposed to high precipitation intensities during rainstorms.

In general, infiltration under field conditions is unsaturated, and water flow may be expected to occur mainly in the soil matrix and not in the macropore system. Thus, low precipitation rates should bring about less pronounced preferential flow. On the other hand, the homogenizing effect of conventional tillage resulting in a smooth, homogeneous infiltration front may be doubted due to the fact that unstructured homogeneous soils do not exist under typical field conditions.

In a recent study, Kern* (2001) evaluated the effect of infiltration rates and tillage on infiltration patterns of Brilliant Blue on a loamy soil at Hilpoltstein (Northern Bavaria). Her results indicate that tillage as well as low infiltration rates increase

* Presented at the 2001 joint meeting of the German Soil Science Society and the Austrian Soil Science Society in Vienna; with permission of A. Kern and W.Durner (Institute of Hydrology, University of Bayreuth and Institute of Geoecology, University of Braunschweig).

**Figure 2.9** Infiltration front of water in a dry Luvisol with conventional tillage after a saturated double-ring infiltration experiment.[90]

**Figure 2.10** Infiltration front of water in a dry Luvisol with reduced tillage after a saturated double-ring infiltration experiment.[90]

matrix flow and decrease preferential flow compared to high infiltration rates and no-tillage. However, preferential flow was observed on all experiment plots (Figure 2.12 and Figure 2.13). Thus, preferential flow of water, nutrients, and pollutants can be modified by tillage systems but not generally avoided.

## 2.7 CONCLUSIONS

Soil structure is an essential soil property that largely determines ecological soil functions. It controls the behavior at the soil–air interface with regard to infiltration, runoff, aeration, erosion, and the local environment of plant roots and edaphon, especially in the topsoil. Heterogeneity of soil structure causes preferential

**Figure 2.11** Infiltration of water into single worm hole in a dry Luvisol with reduced tillage following a saturated double-ring infiltration experiment.[90]

flow in soils, which may be the principal cause of groundwater pollution by agrochemicals.

Tillage greatly affects soil structure in topsoil and, to a certain degree, in the subsoil. In most studies, reduced tillage exhibits positive effects on infiltration, resulting in reduced runoff and erosion. On the other hand, preferential flow is facilitated, and groundwater pollution risks are increased. Conventional tillage results in homogenization of the topsoil. This may decrease preferential flow. However, transport in fast-transport systems cannot be avoided under typical field conditions.

Optimization of management systems will require further experimental studies. In future studies, field experiments should be supported by simulation studies. Care must be taken to ensure that the choice of the most appropriate model matches the specific research objectives. First models that take into account soil structure and structural changes due to tillage impacts are available and have been tested in several studies.[15,64,71,72]

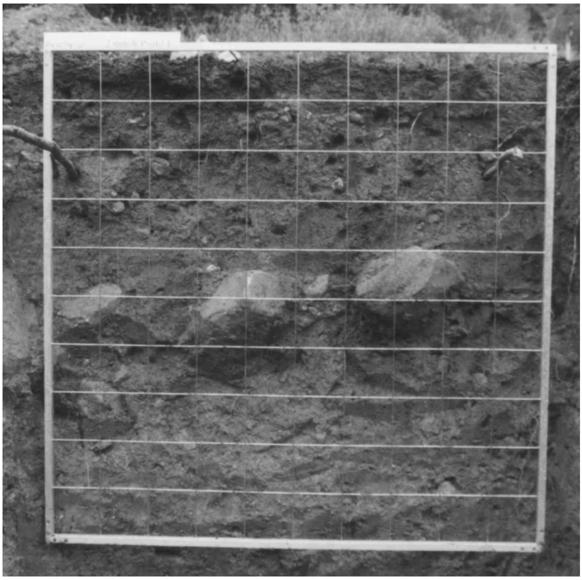

**Figure 2.12** Distribution pattern of Brilliant Blue in a tilled loamy soil after 30 mm infiltration of water at a rate of 2 mm/day.*

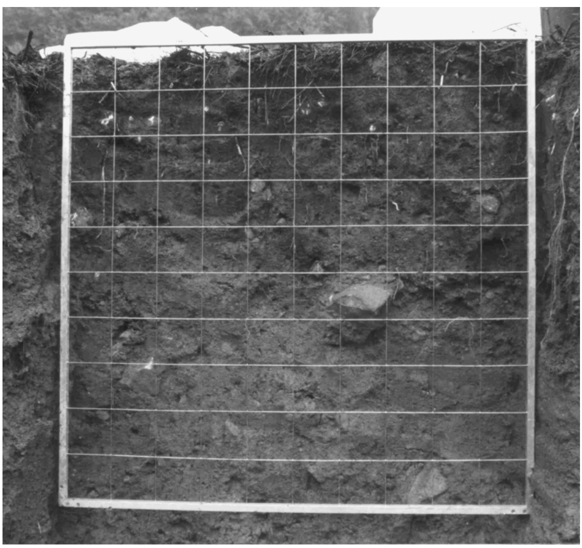

**Figure 2.13** Distribution pattern of Brilliant Blue in an untilled loamy soil after 30 mm infiltration of water at a rate of 2 mm/day).*

* Presented at the 2001 joint meeting of the German Soil Science Society and the Austrian Soil Science Society in Vienna; with permission of A. Kern and W.Durner (Institute of Hydrology, University of Bayreuth and Institute of Geoecology, University of Braunschweig).

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